Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Suzan Bayhan*, Esa Hyytiä, Jussi Kangasharju* and Jörg Ott

*University of Helsinki and Aalto University, Finland

MWN-I04: Wireless Relay Networks,
17:15-18:00 ICC Capital Hall Interactive 2

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Mobile opportunistic networks

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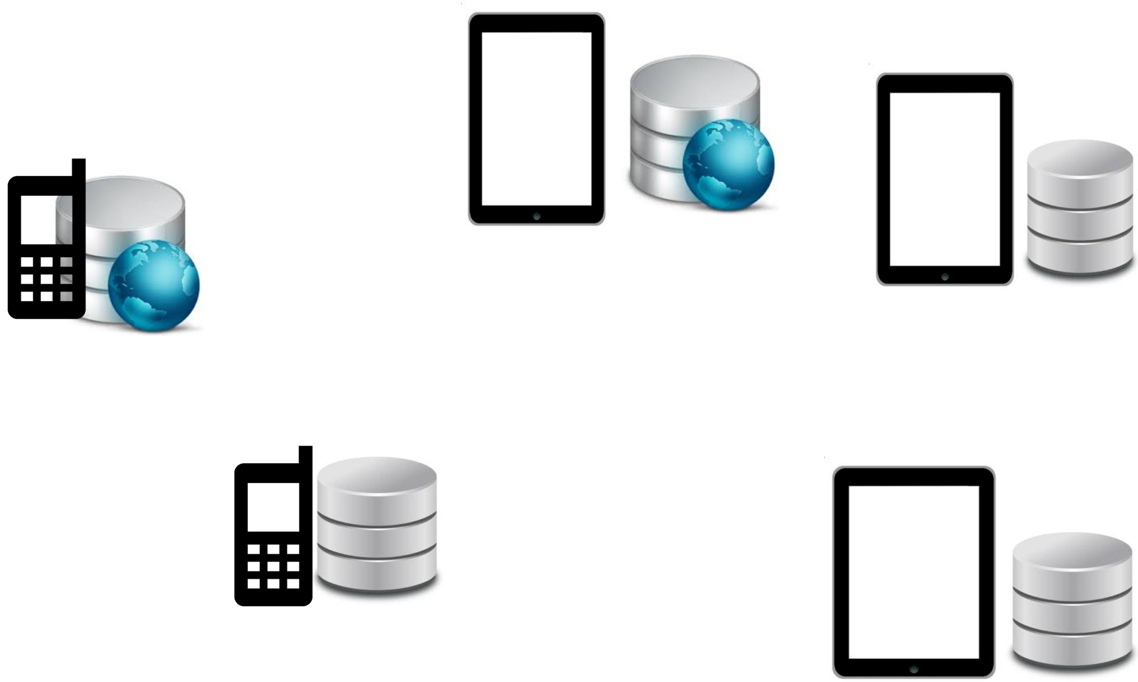
Many mobile devices with different types of content stored locally



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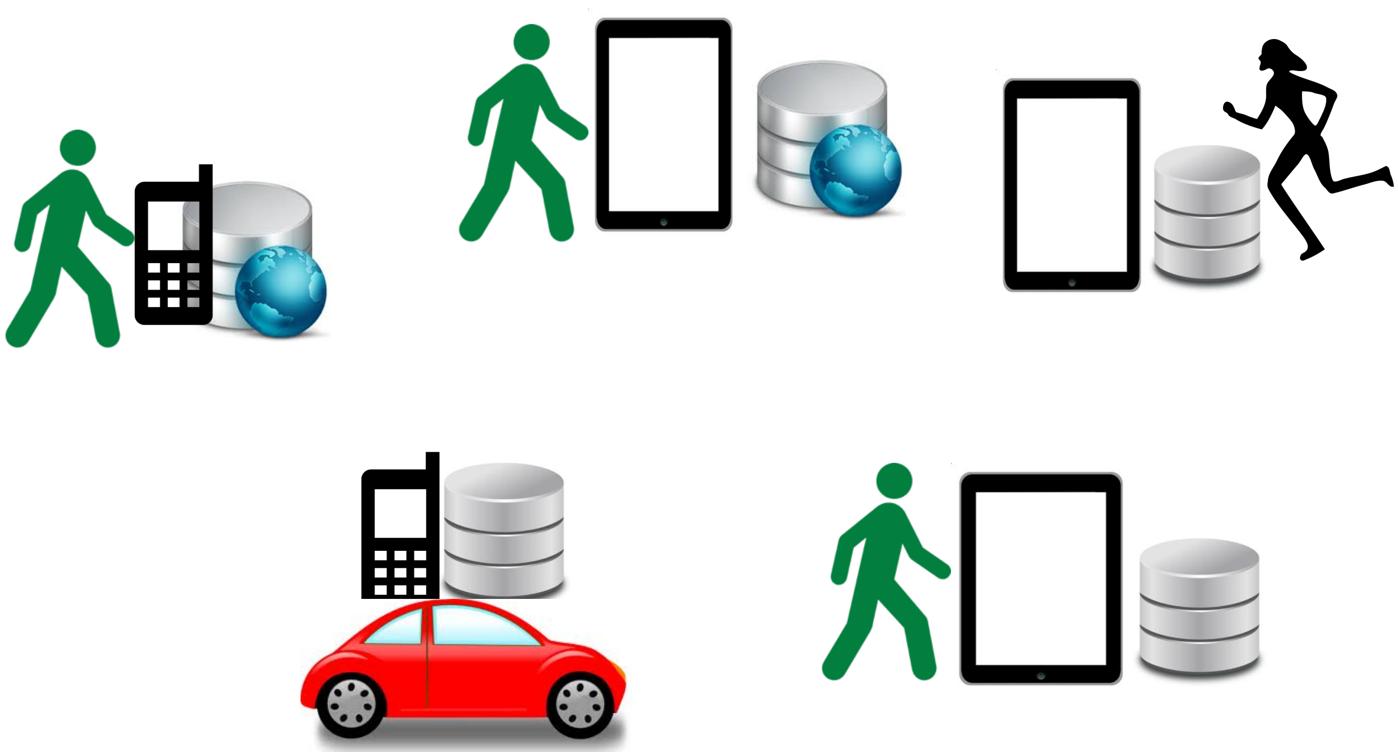
Carried by users



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Mobile opportunistic networks

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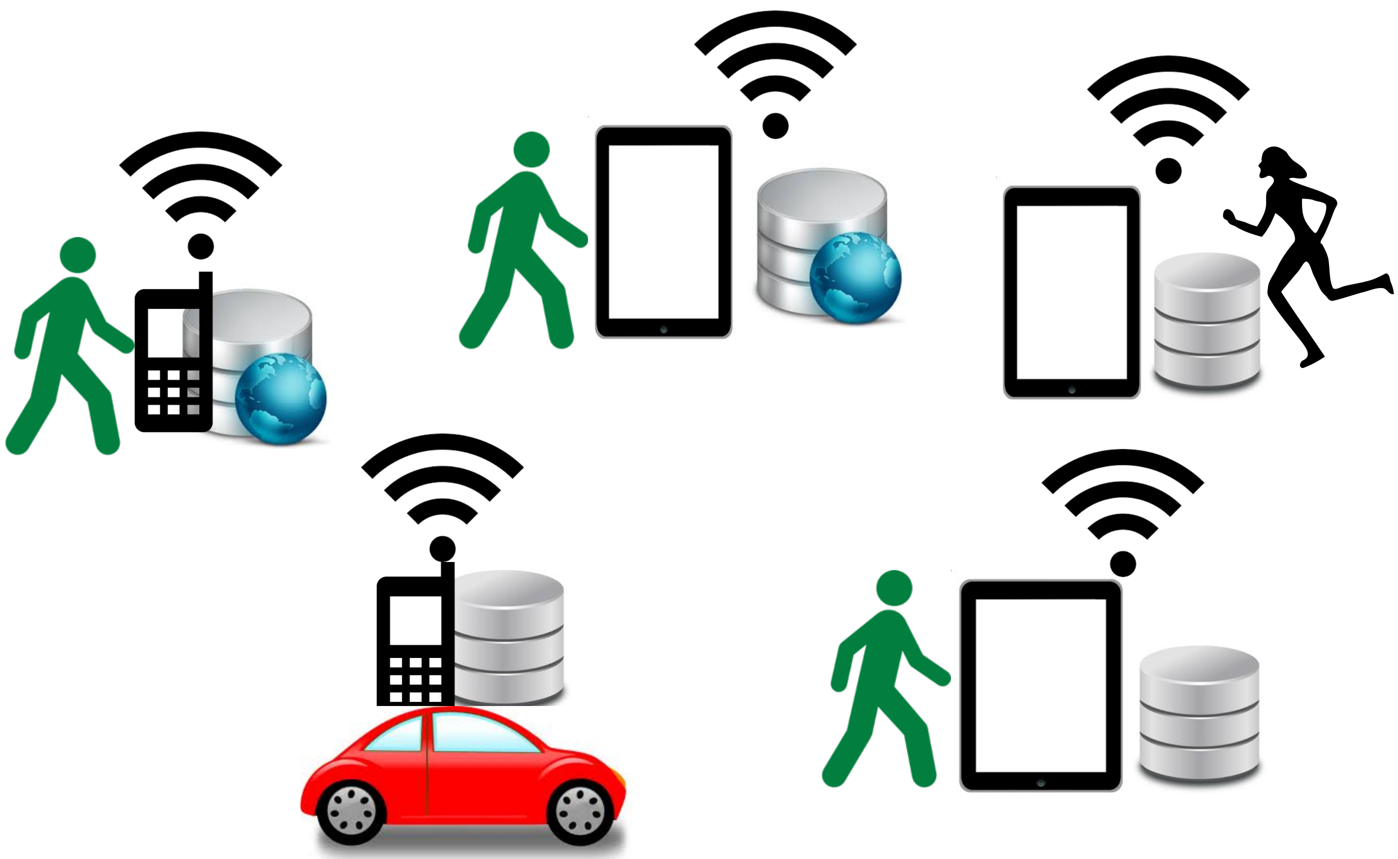
Short range radio, e.g., Bluetooth, Wifi Direct



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Opportunistic communication
store-carry-forward

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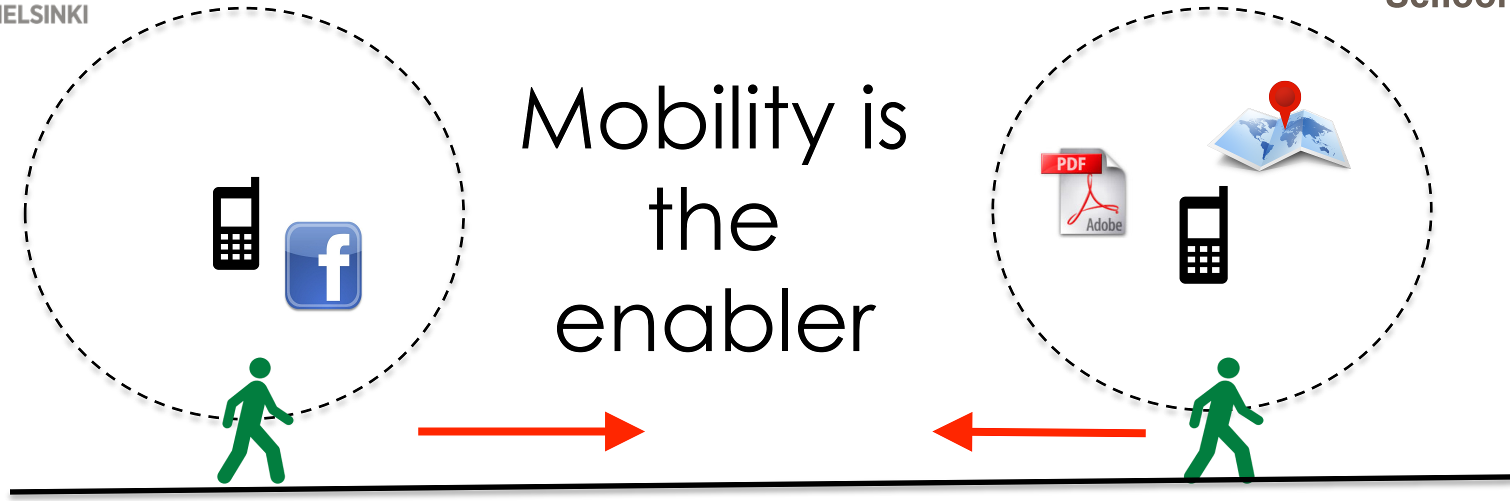
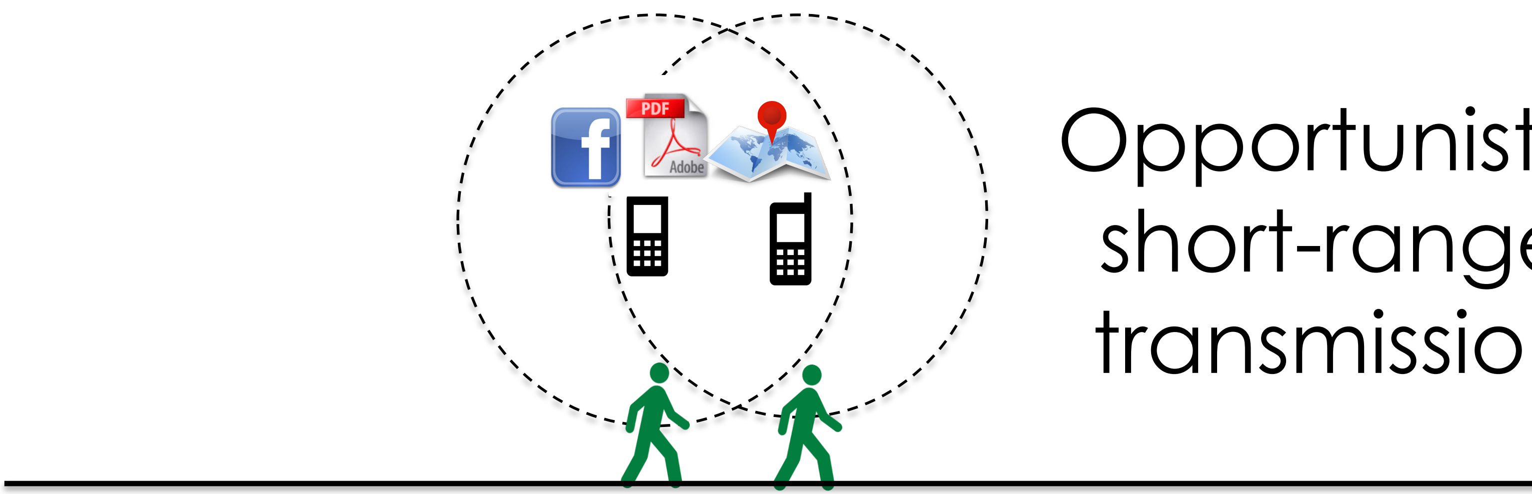


Mobility is the enabler



Opportunistic short-range transmission

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Hop limitations are applied to keep routing scalable and resource-efficient.

Source node	Destination node	Relaying nodes	Hop limit

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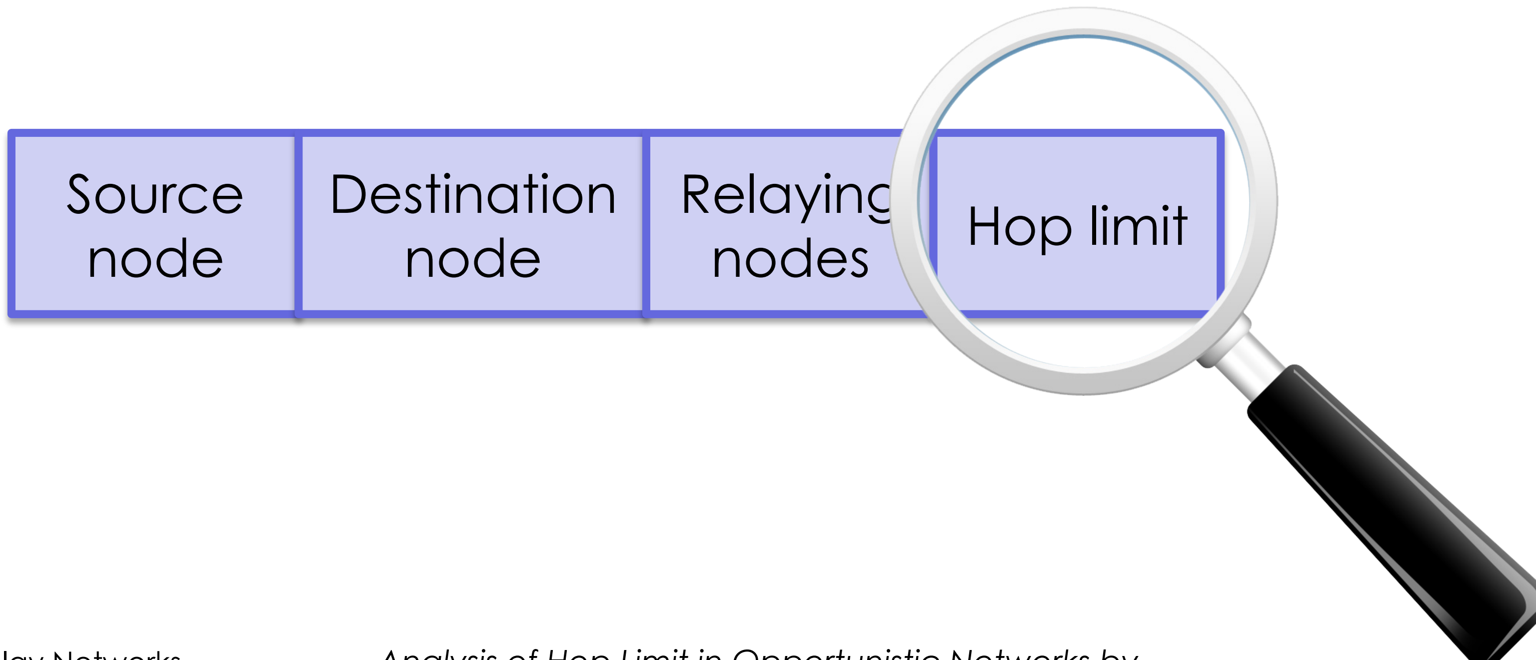
Hop limitations are applied to keep routing scalable and resource-efficient.



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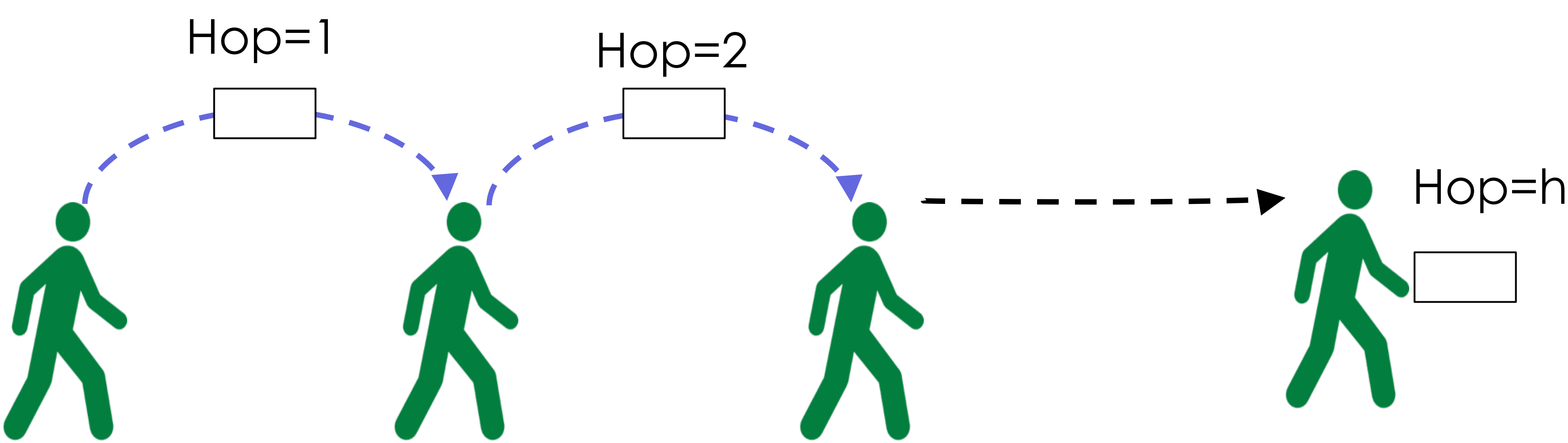
Hop-Limited Routing

A message can be forwarded to **at most h hops**



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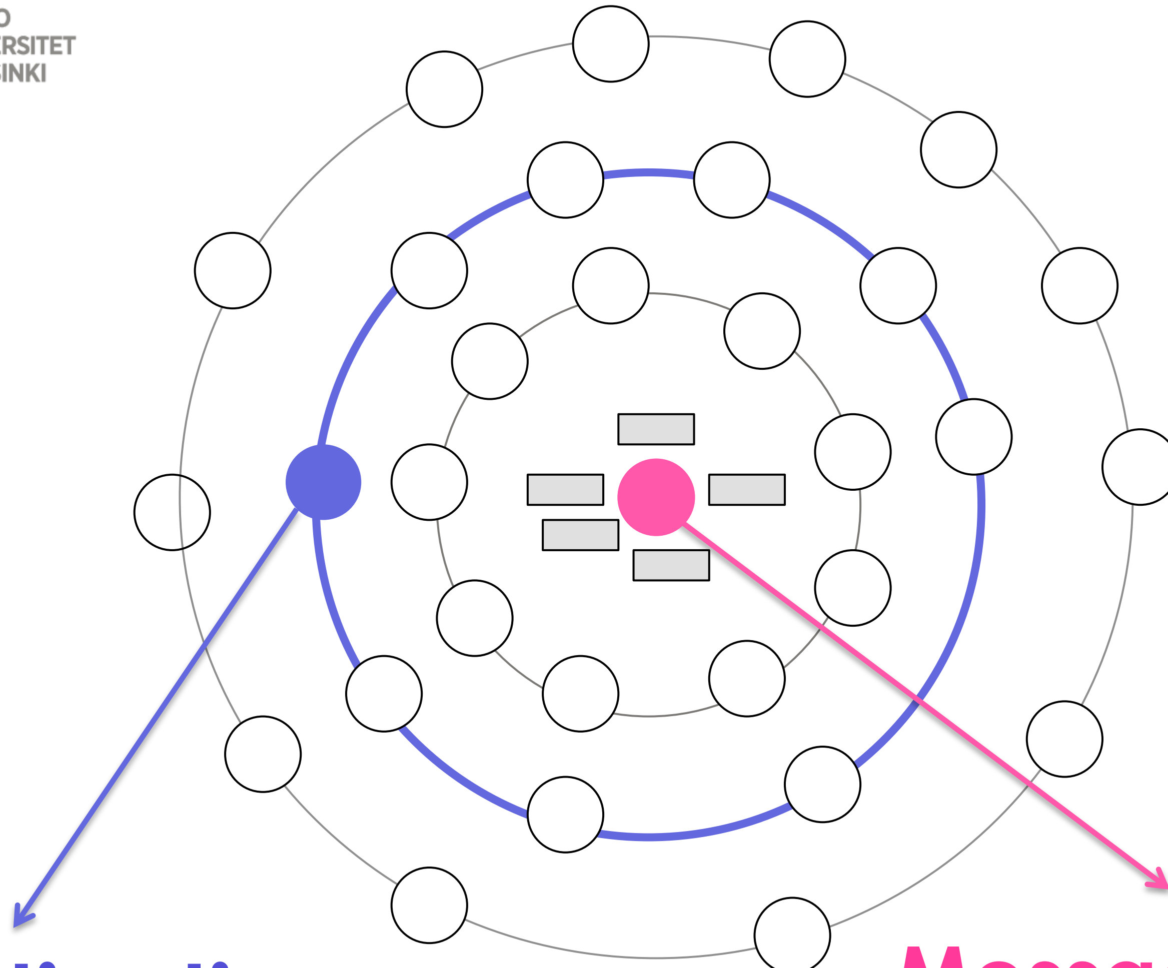
Hop = 0



Destination

Message created hop=0

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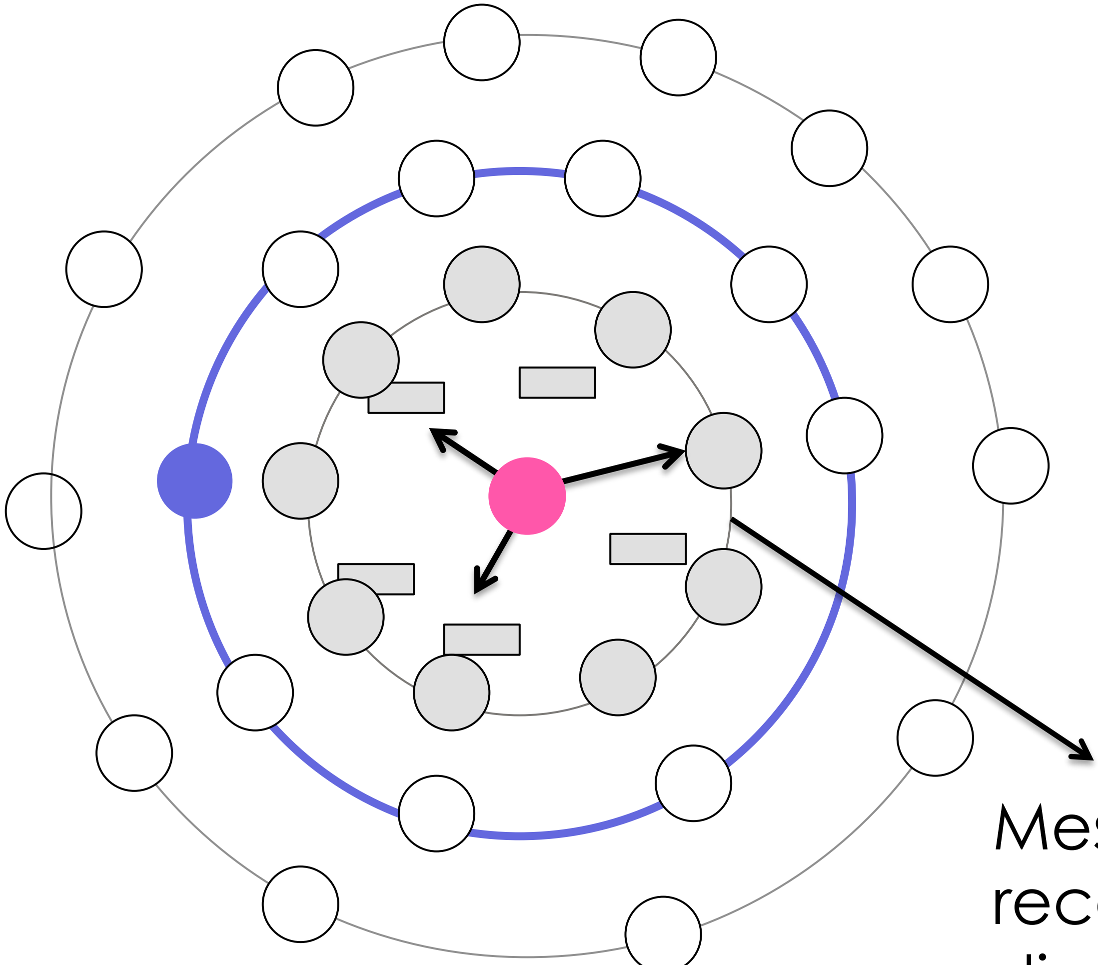
Hop = 1



Message received by direct neighbors

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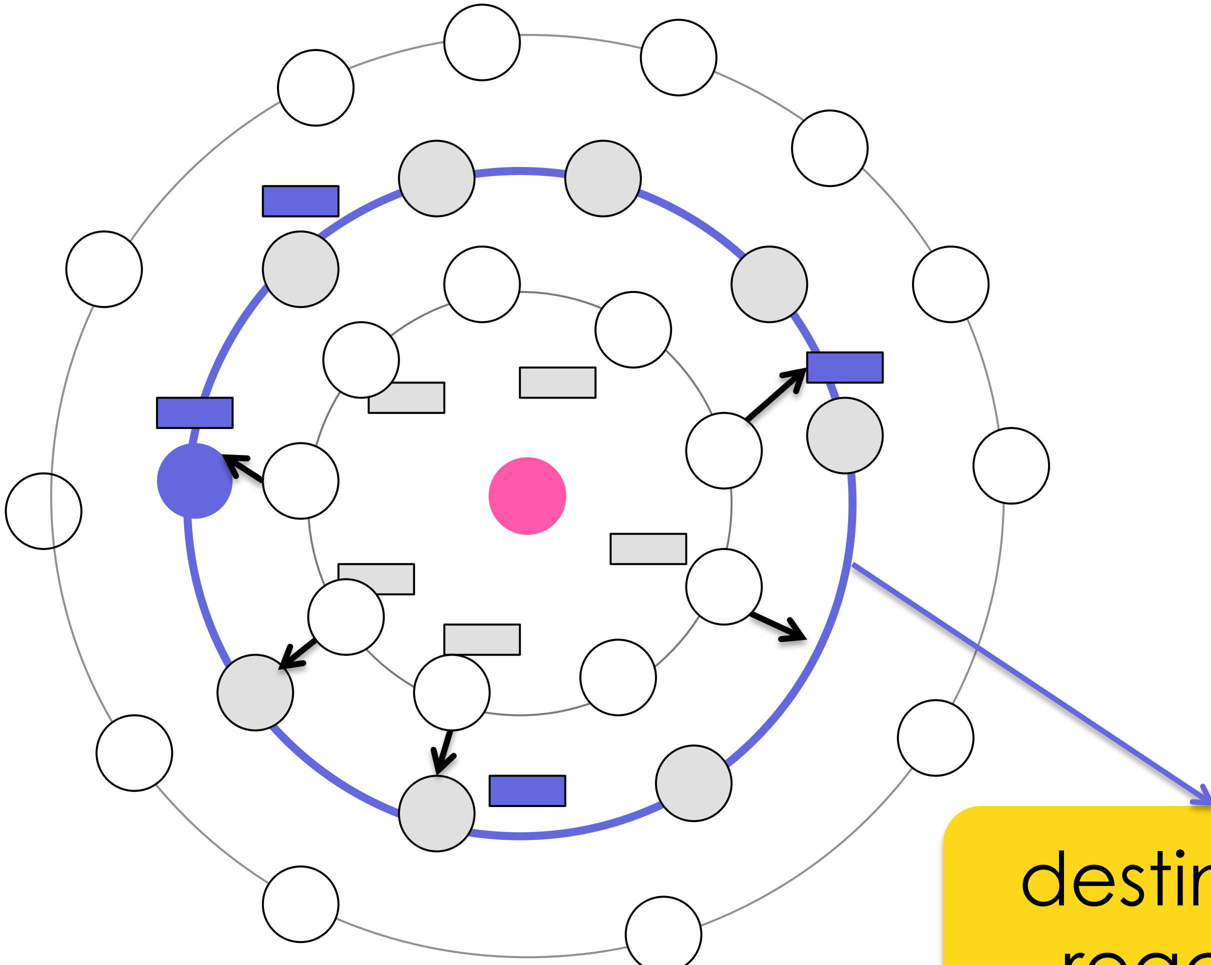
Hop = 2



destination reached

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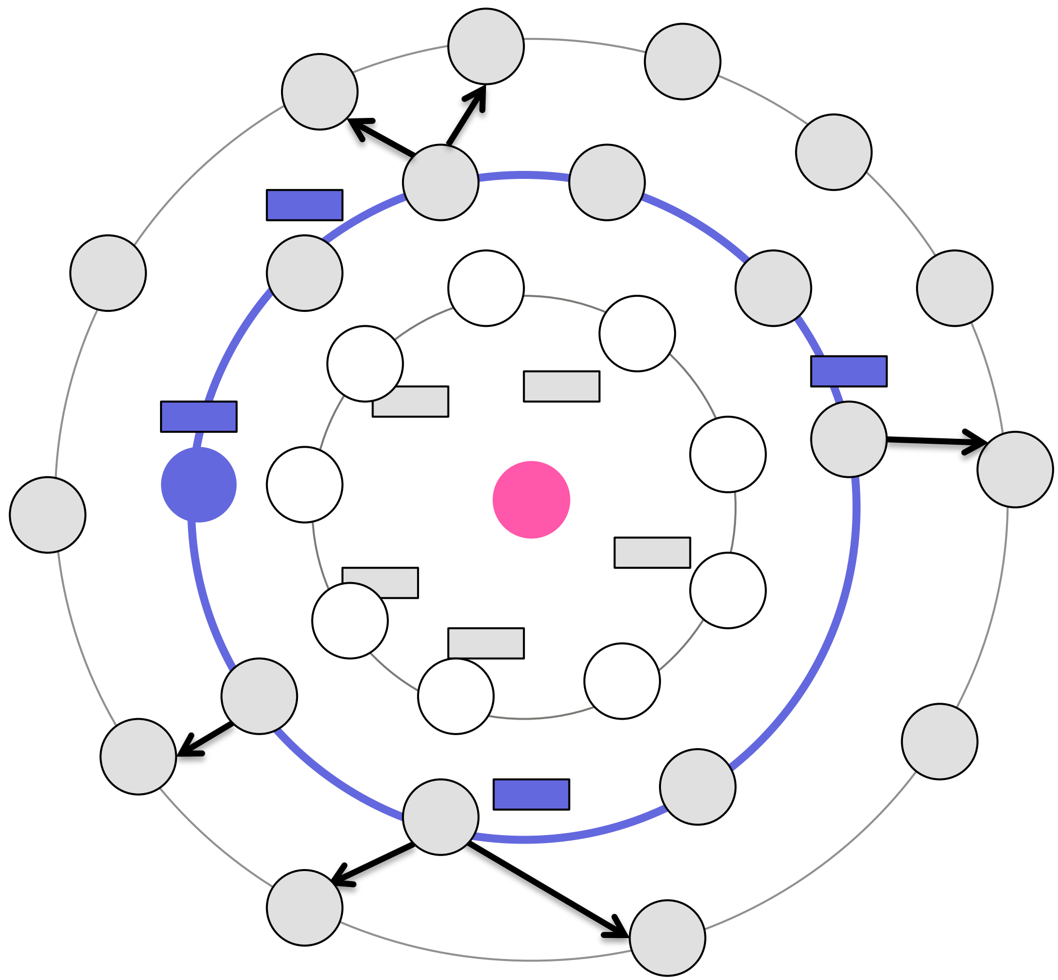
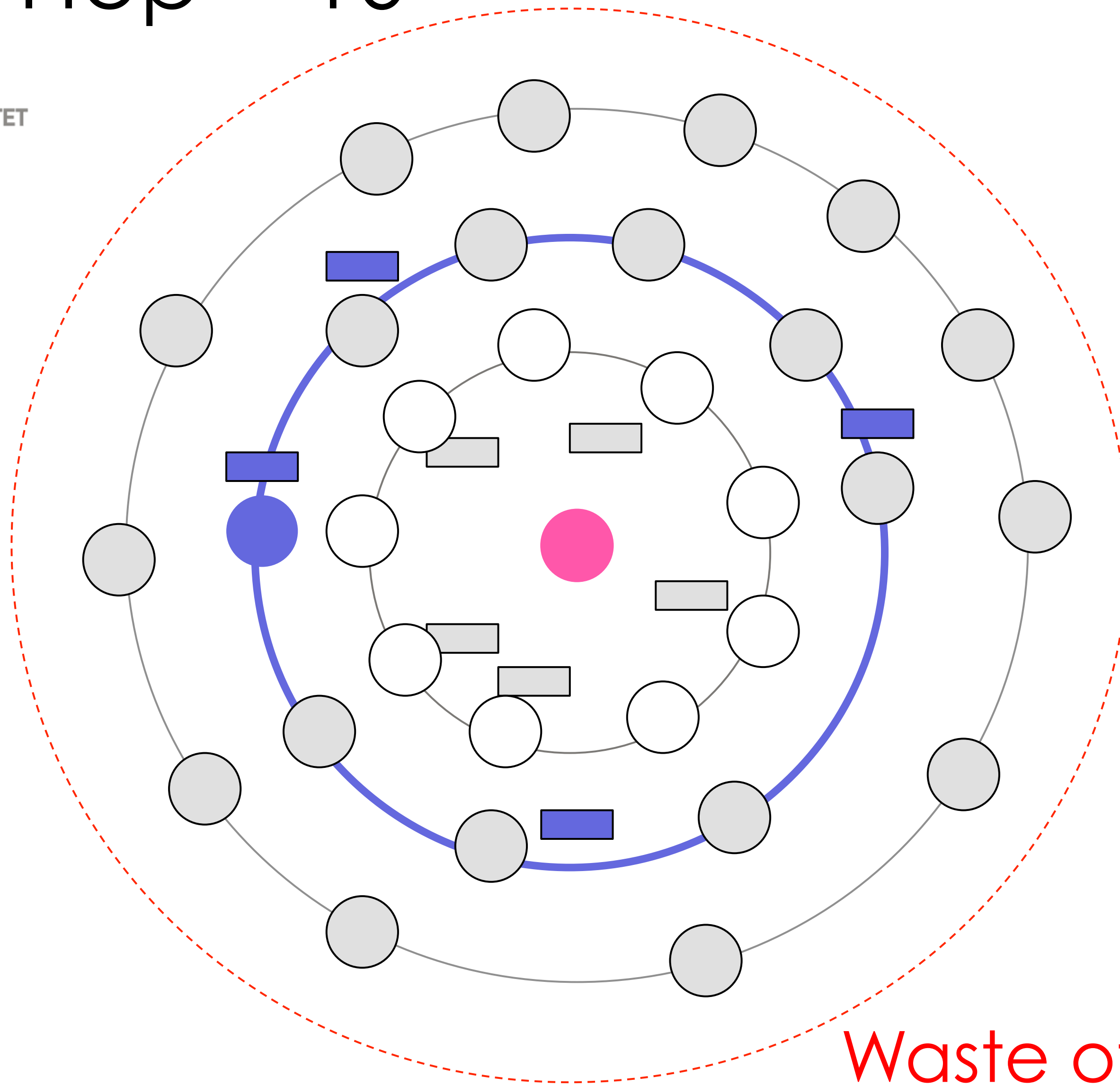
Hop = 3



Other nodes may not be aware of the delivery of the message to the destination.

Hop = 10



Waste of resources

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How does hop limit affect opportunistic routing?

1. average time to send a packet
2. fraction of nodes reachable
3. delivery ratio

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http://www.lettercult.com/archives/3196

analysis approaches

Static graph

Time-aggregated graphs

Simulations

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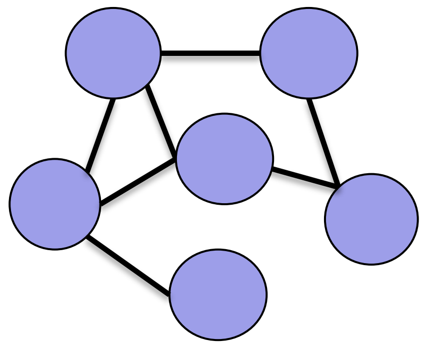
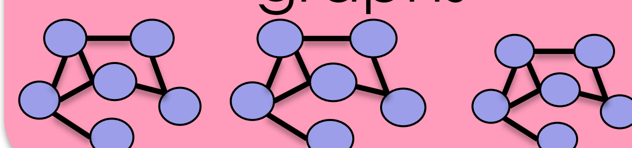
Corresponding network topology

Contact trace



Static graph

Time-aggregated graphs



Capacity Analysis for h=1,…,H

or simulate!

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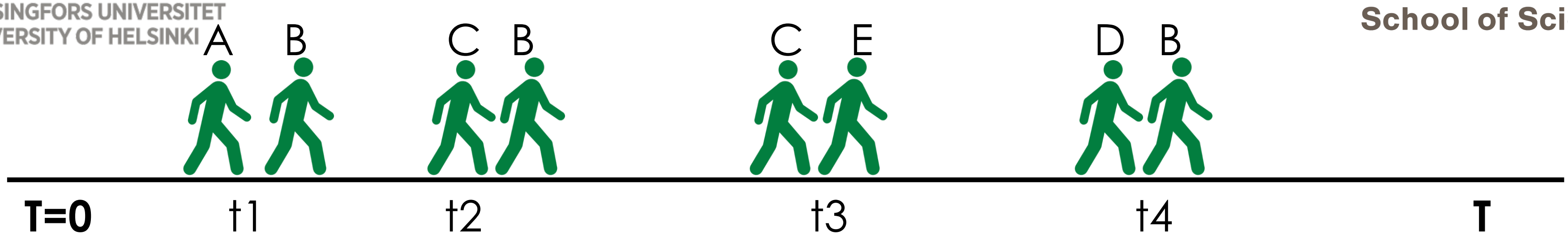
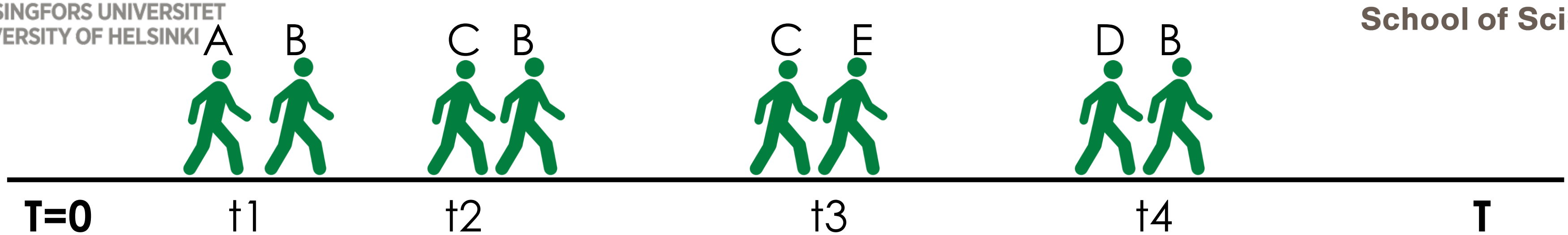
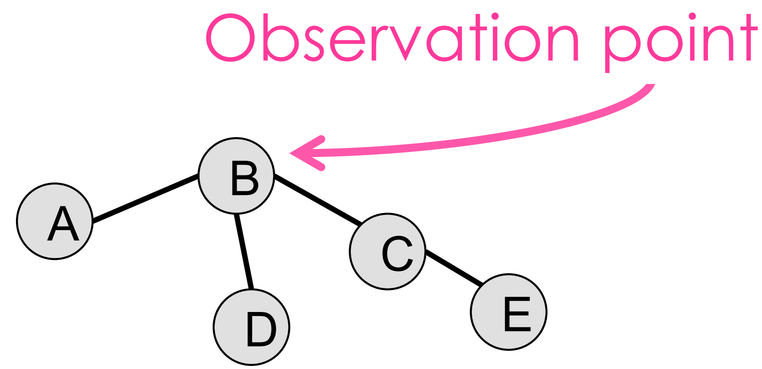
Network topology generation



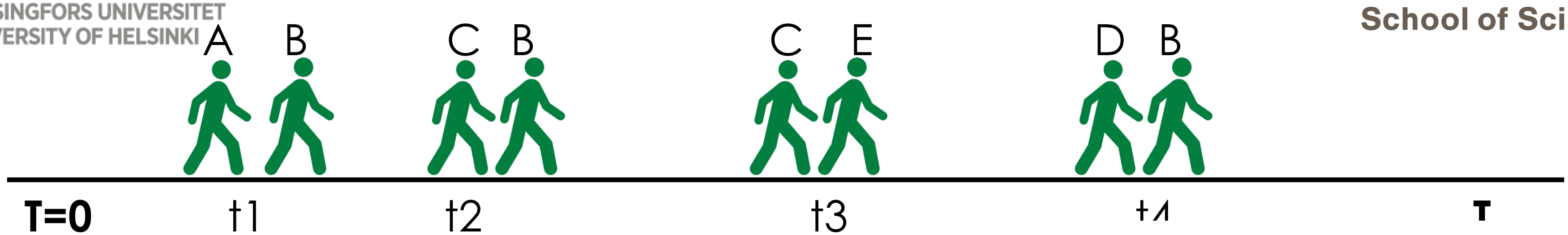
Network topology generation

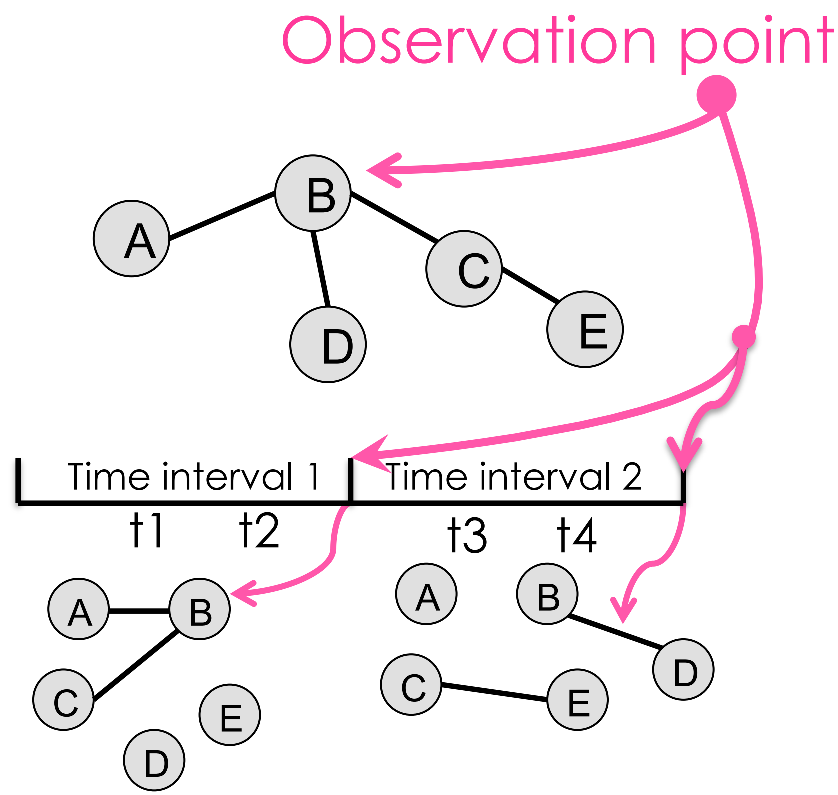


<u>Approach 1:</u> Aggregate all contacts in the trace, and create a static graph to represent network topology → **Static graph**



Network topology generation





<u>Approach 1:</u> Aggregate all contacts in the trace, and create a static graph to represent network topology → **Static graph**

<u>Approach 2:</u> Instead of one single graph, observe the network in several time points, and create the network topology → **Time-aggregated graph**

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Static vs. Time-Aggregated graphs

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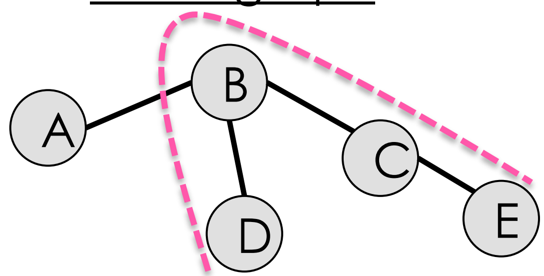
<u>Static graph</u>



D → B → C → E in static graph

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Static vs. Time-Aggregated graphs

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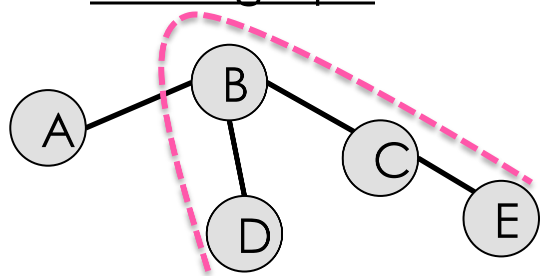
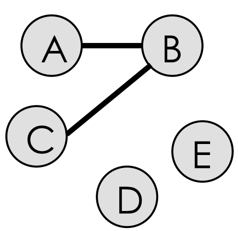
Static graph

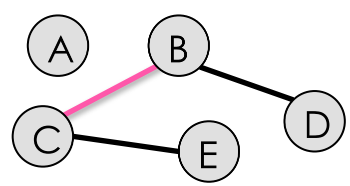


D → B → C → E in static graph

Time interval 1



Time interval 2



Only D → B in this second graph

B→ C link is missing

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Static vs. Time-Aggregated graphs

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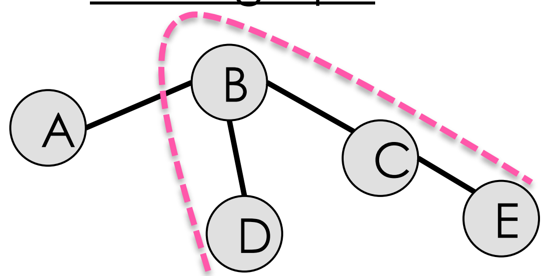
Static graph



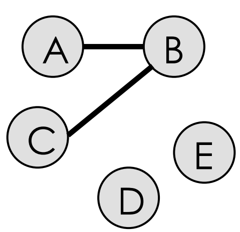
D → B → C → E in static graph

Time-aggregation results in **loss of temporal dynamics** but simplistic

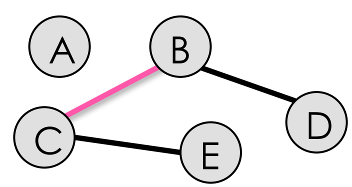
Static graph **overestimates** the connectivity and hence the capacity

How much
does it affect?

Time interval 1



Time interval 2



Only D → B in this second graph
B→ C link is missing

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IEEE/ACM TRANSACTIONS ON NETWORKING, VOL. 10, NO. 5, OCTOBER 2002 613

Computing Shortest Paths for Any Number of Hops

Roch Guérin, *Fellow, IEEE,* and Ariel Orda, *Senior Member, IEEE*

***Abstract*—In this paper, we introduce and investigate a "new" path optimization problem that we denote the *all hops optimal path* (AHOP) problem. The problem involves identifying, for all hop counts, the optimal, i.e., minimum weight, path(s) between a given source and destination(s). The AHOP problem arises naturally in the context of quality-of-service (QoS) routing in networks, where routes (paths) need to be computed that provide services guar-**

over paths that are capable of meeting them (see [1] for a comprehensive survey). Furthermore, for efficiency purposes, it is also important to do so at the minimum possible cost to the network.

From an algorithmic standpoint, this calls for algorithms that compute paths satisfying specific (service) constraints, while

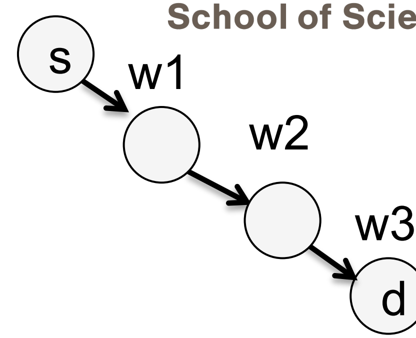
AHOP

All Hops Optimal Paths

All Hops Optimal Path (AHOP) Problem: For a given source node $s \in \mathcal{V}$ and maximal hop count H, $H < N$, find, for each hop count value $h, 1 \leq h \leq H$, and destination node $u \in \mathcal{V}$, an h-hop constrained optimal path between s and u.

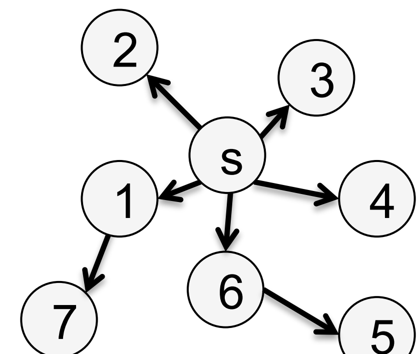
AHOP for capacity analysis

Q1: Average time to send a packet



Path length

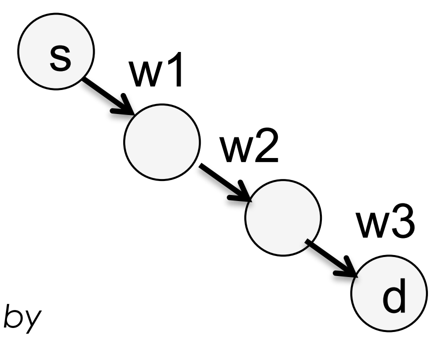
Q2: Fraction of nodes reachable



Size of the connected component

Q3: Delivery ratio

Probability of the existence of a path



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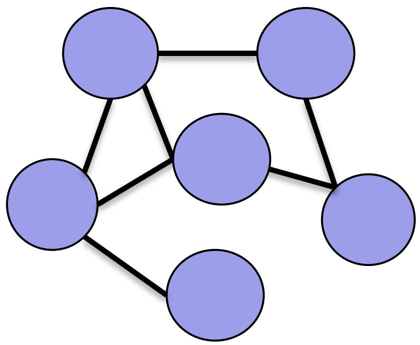
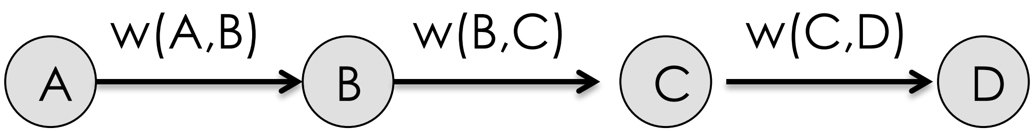
AHOP analysis





p: A → B → C → D

- Optimal path **p* from A to D** is the path with **minimum w(p)** among all paths from A to D.
- Hop-limited optimal path p* is p_h^* where **length(p_h^*) <= h**
- Given the edge weights, what is the weight of **p**, **w(p)**?

Edge weights

- w(p) = w(A,B) + w(B,C) + w(C,D) → ***Additive*** *weights*
- w(p) = max{w(A,B), w(B,C), w(C,D)} → ***Bottleneck*** *weights*

Additive weight: Path weight = routing delay

- weight of an edge: **inter-contact time** between the corresponding nodes

Bottleneck weight (capacity): A routing scheme should choose the paths that will highly probably exist → *most probable* paths.

- weight of an edge: the inverse of the **number of encounters** between the corresponding nodes

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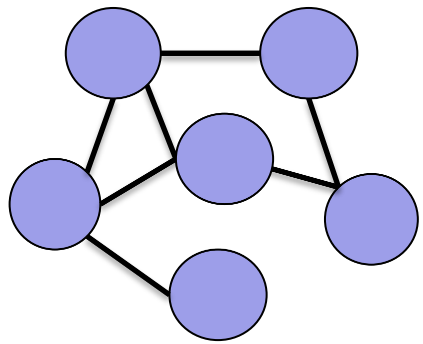
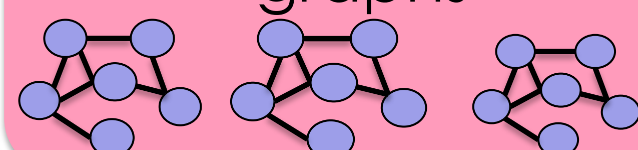
Corresponding network topology

Contact trace



Static graph

Time-aggregated graphs



AHOP

for h=1,...,H

Bottleneck

Additive

or simulate!

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NumeRical Evaluation

R for graphs and AHOP (*timeordered* package Benjamin Blonder)

ONE for simulations

TABLE I

HUMAN CONTACT TRACES USED IN THE ANALYSIS.

Trace	Duration	# of devices (n)	Context
Infocom05	≈3 days	41	Conference participants
Cambridge	≈11 days	36	1st and 2nd year undergraduate students
Infocom06	≈4 days	78 (and 20 stationary devices)	Conference participants

CRAWDAD http://crawdad.cs.dartmouth.edu/

Community Resource for Archiving Wireless Data At Dartmouth

Static analysis: hop limit vs. capacity

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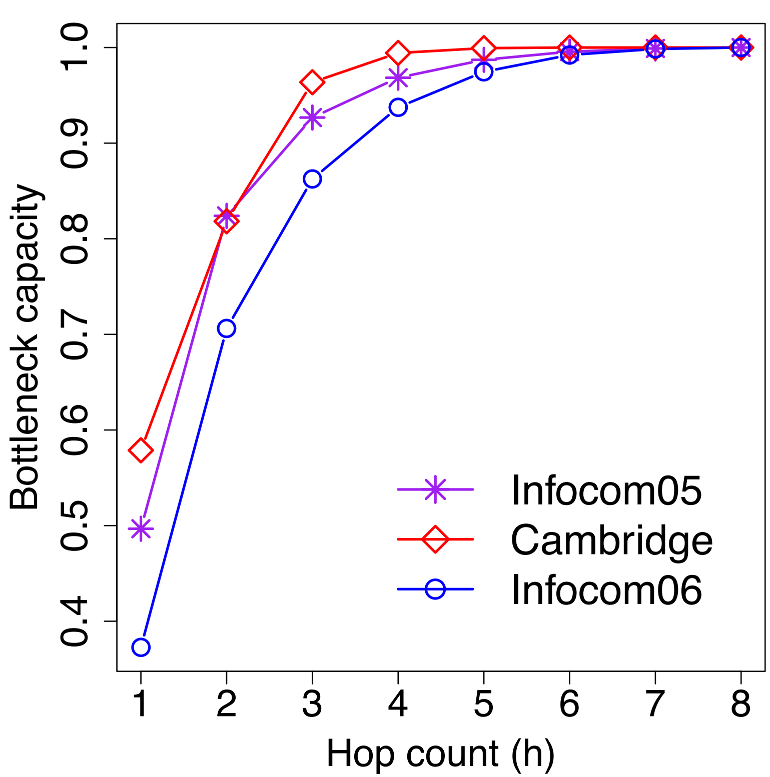
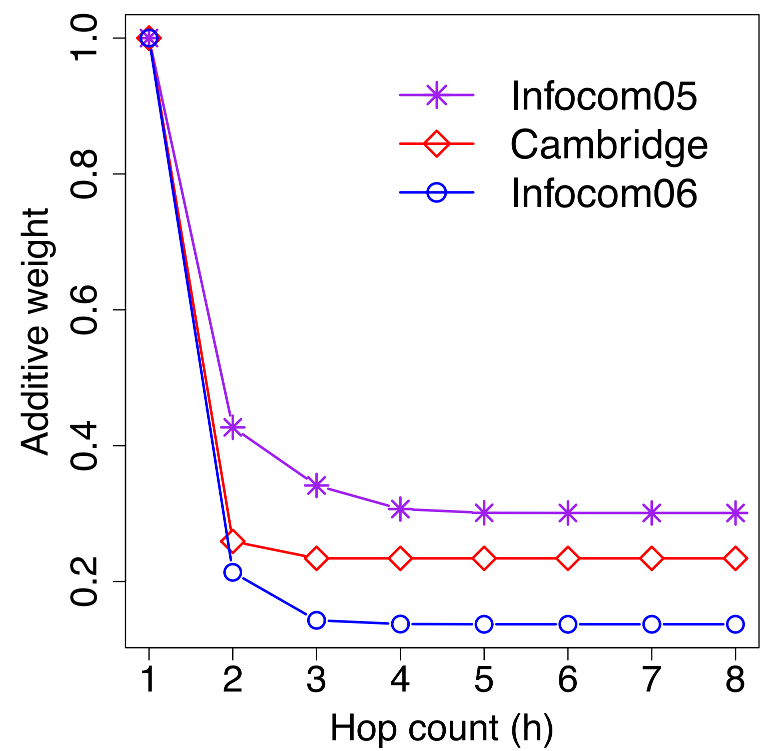
Normalized delivery success



Normalized delay



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Static analysis: hop limit vs. capacity

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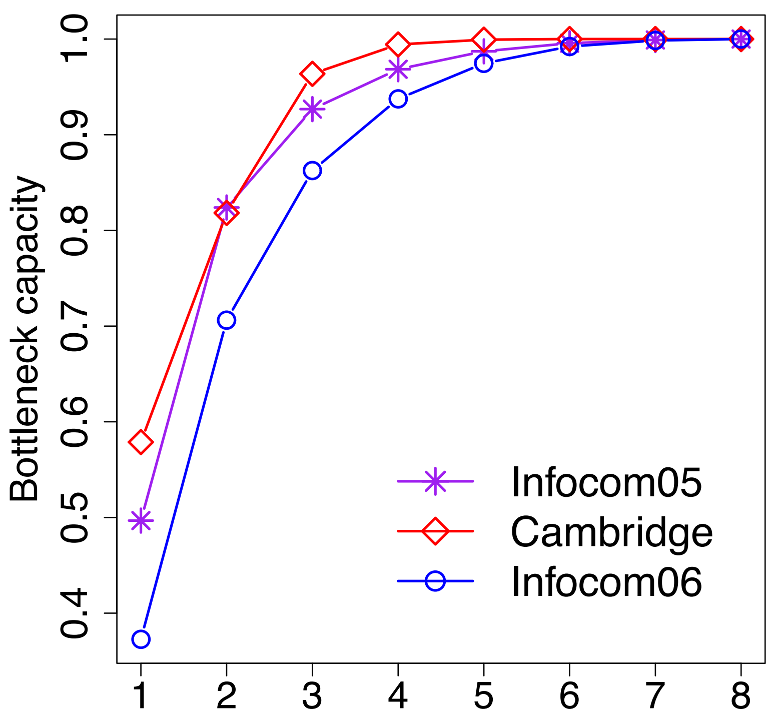
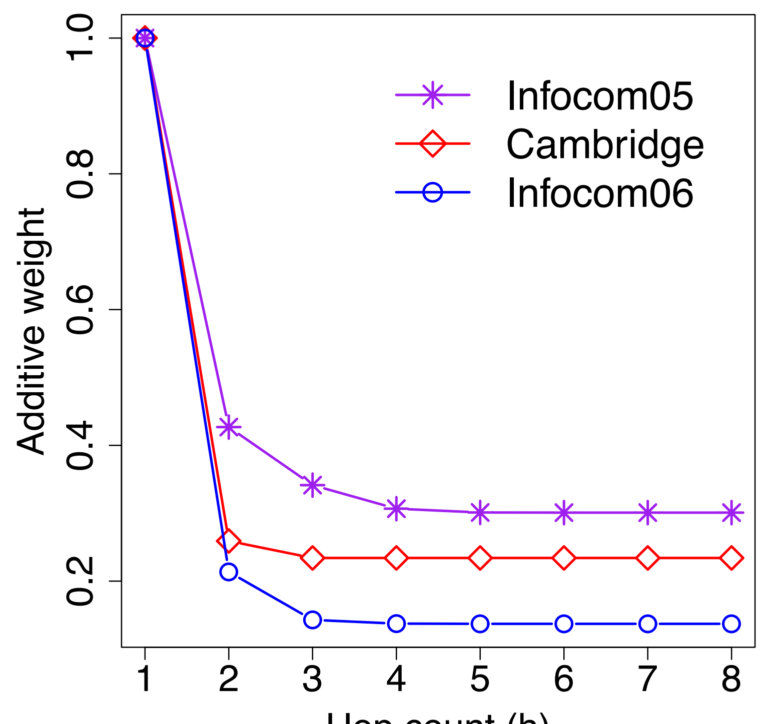
Normalized delivery success



Normalized delay



Delivery ratio increases while delay decreases with increasing h

Static analysis: hop limit vs. capacity

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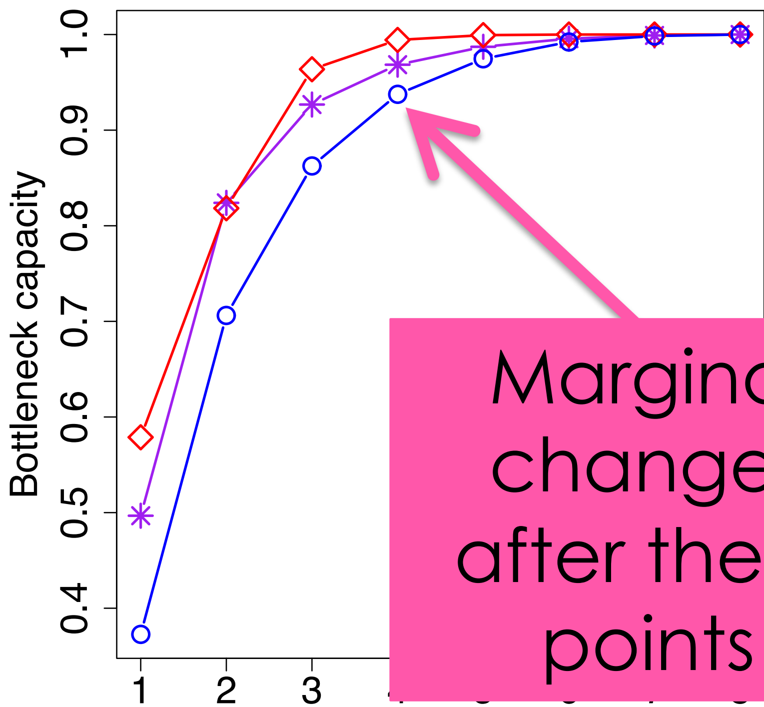
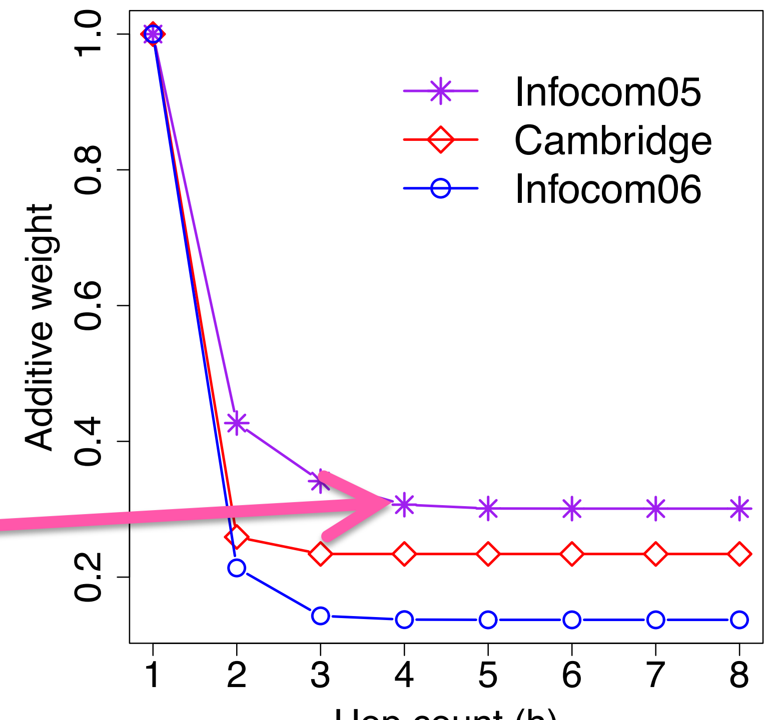
Normalized delivery success



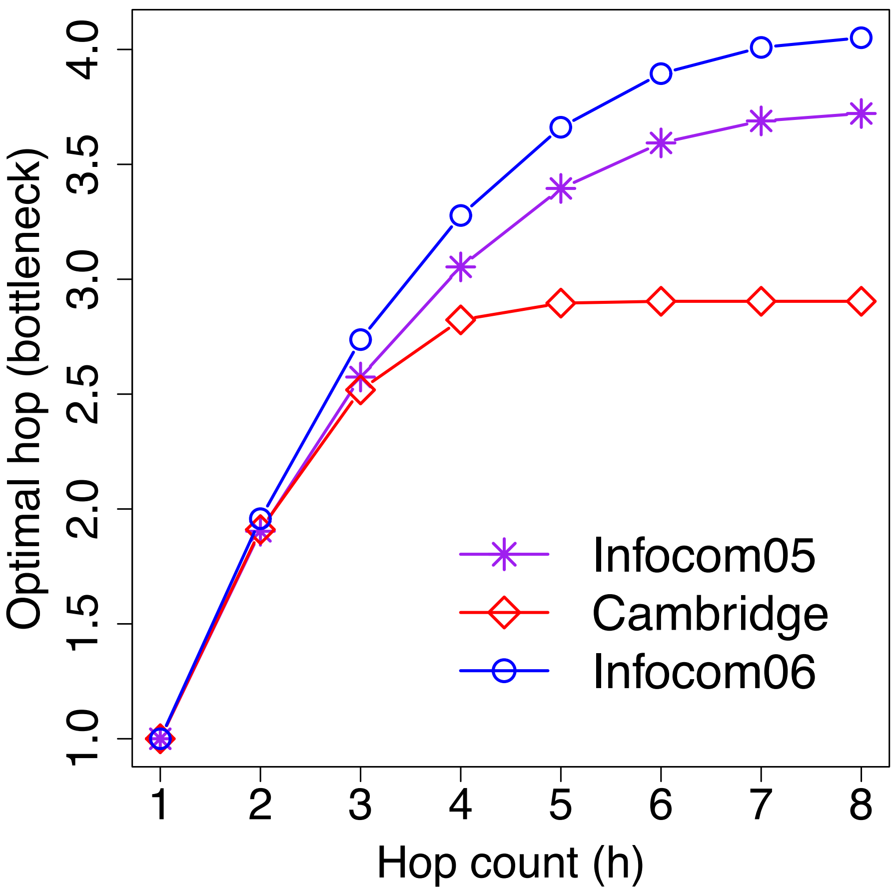
Normalized delay

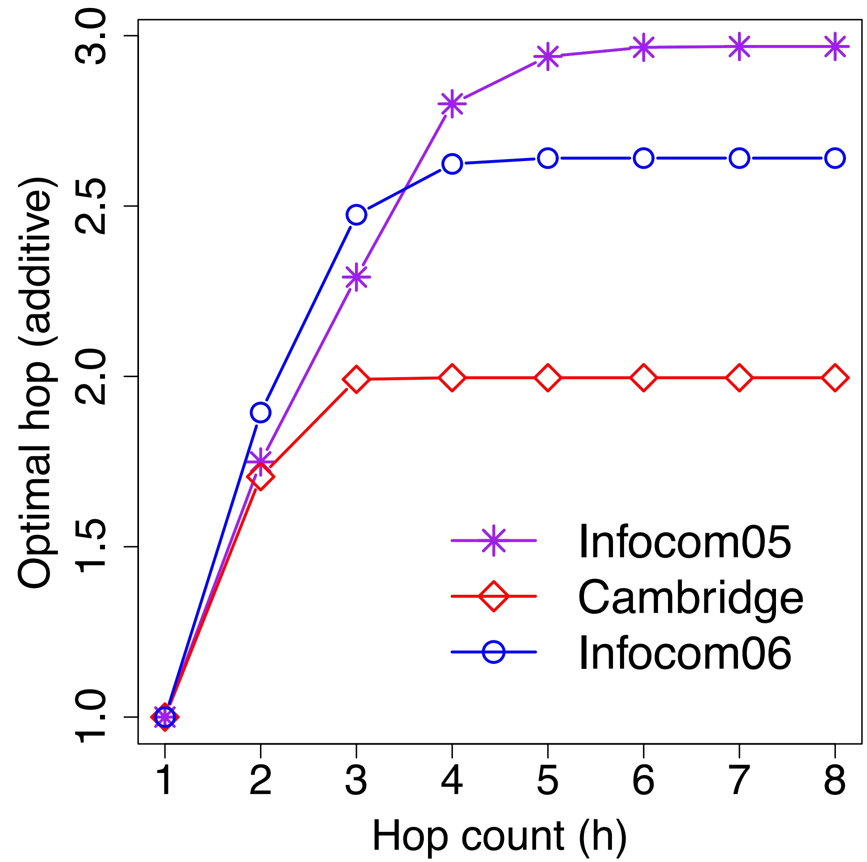


Marginal changes after these points

Delivery ratio increases while delay decreases with increasing h

Static analysis: optimal hop





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Static analysis: optimal hop

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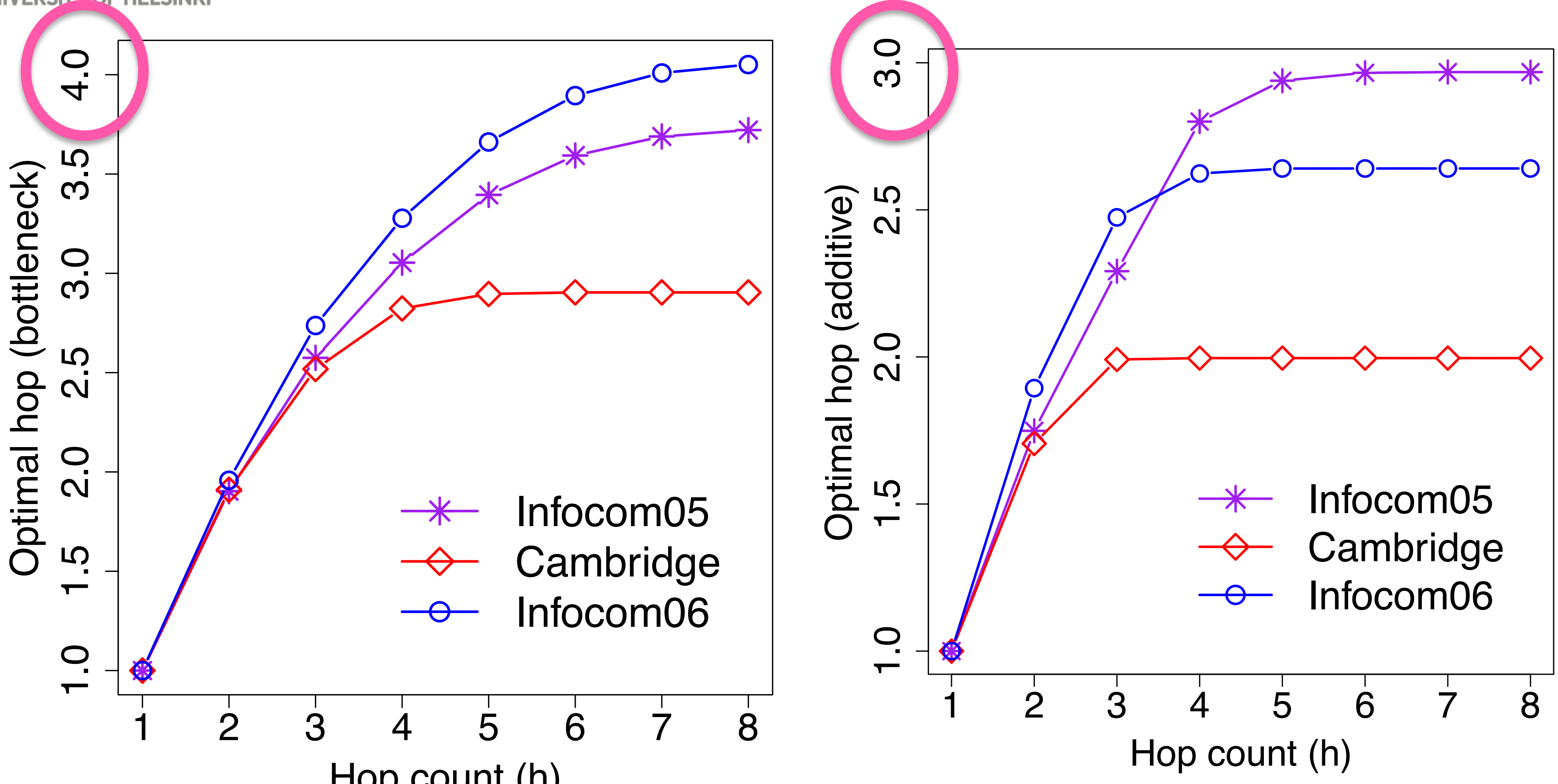

Very low hop counts

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Revisiting our research questions

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1 average time to send a packet

- Nodes can be reached faster by relaxing hop count
- Improvement vanishes after several hops
- Optimal hop counts (total path delay): 2-3 hops

2 fraction of nodes reachable

The first two hops are sufficient to reach every node from every other node.

3 delivery ratio

increases significantly if at least two hops are allowed, and stabilizes after h approx. 4.

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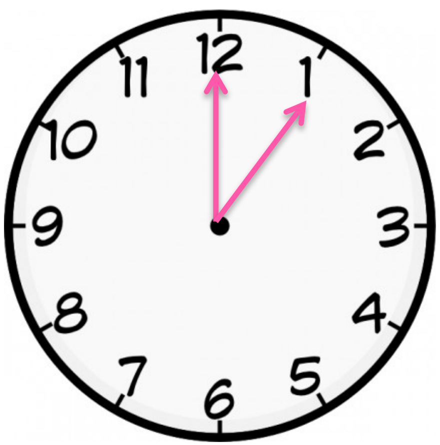
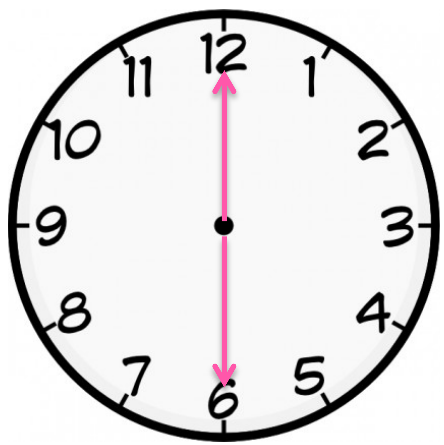
Time-aggregated graphs

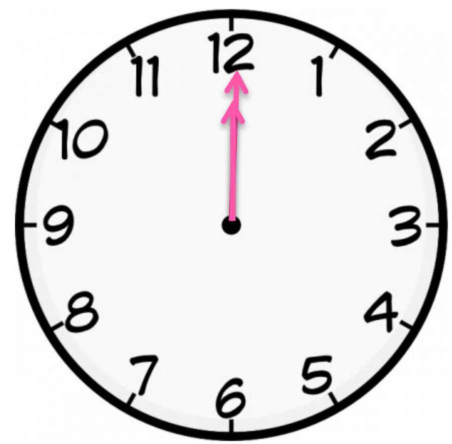
Three aggregation windows



Short : 1 h



Medium: 6 h



Long: 24 h

Time-aggregated graphs
Optimal hop count over time

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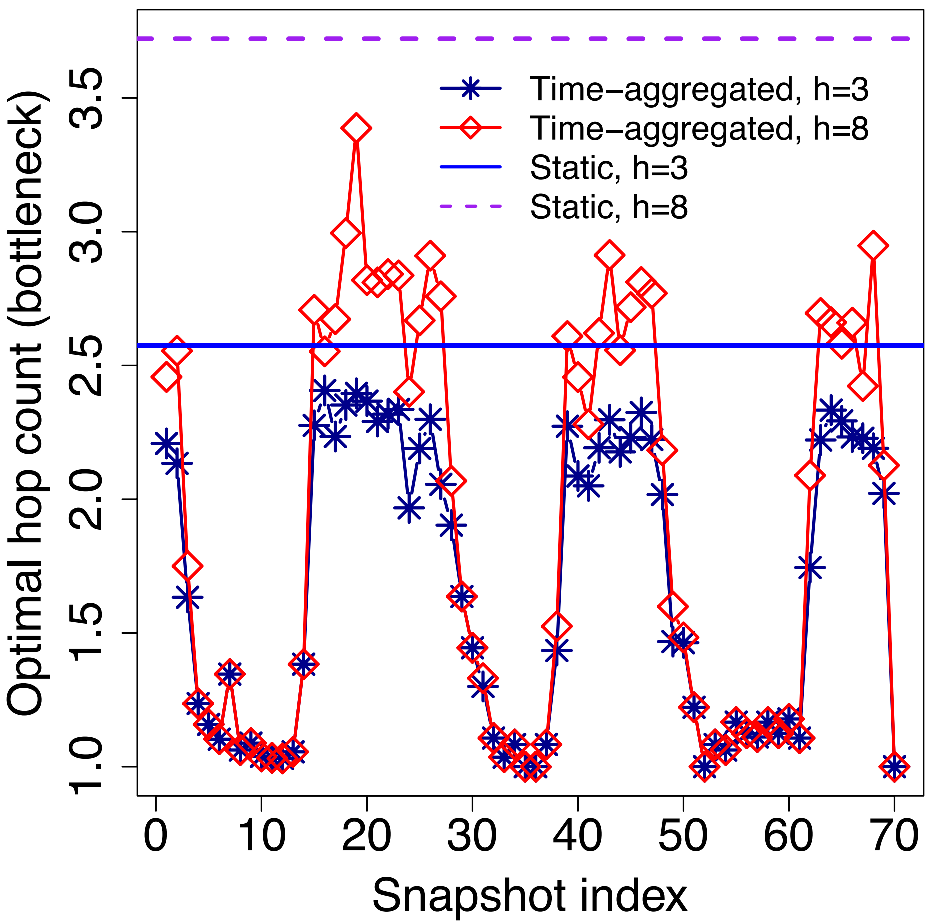
Infocom05, short



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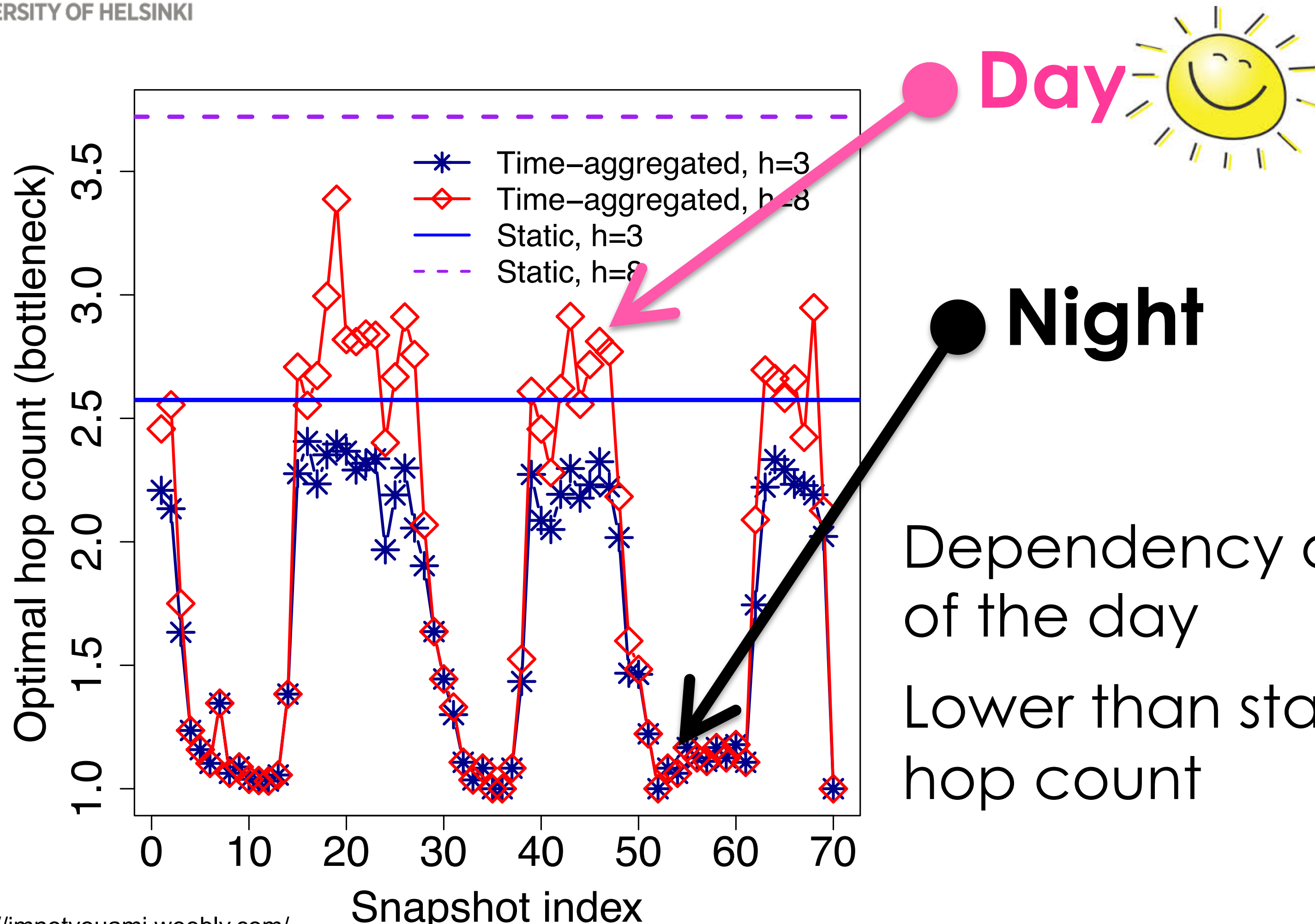
Time-aggregated graphs
Optimal hop count over time



Dependency on the time of the day

Lower than static optimal hop count

http://imnotyouami.weebly.com/
http://commons.wikimedia.org

MWN-I04: Wireless Relay Networks
Bayhan *et al.*, IEEE ICC 2015

Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Time-aggregated graphs
Hop vs. reached fraction

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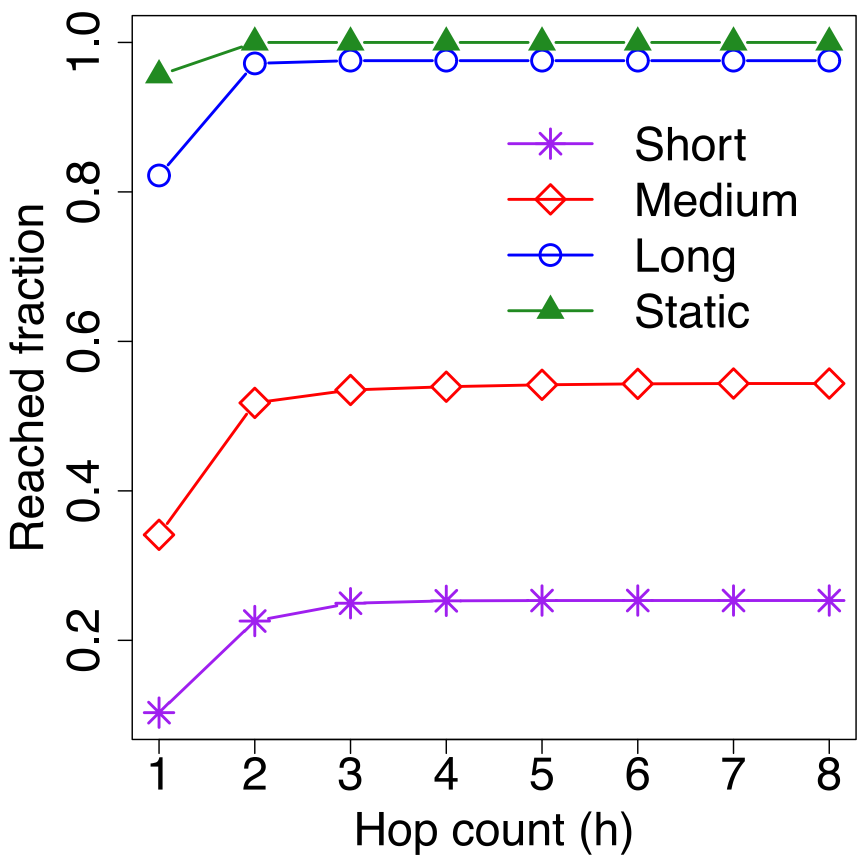

Larger time-window, higher reached fraction

Acc. to static analysis, 2 hops are enough to reach all. But lower connectivity for others.

Trend is the same (h=2 achieves most of the gains of multi-hop routing).

Bayhan *et al.*, IEEE ICC 2015 *Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs*

Network snapshots
Hop count vs. capacity

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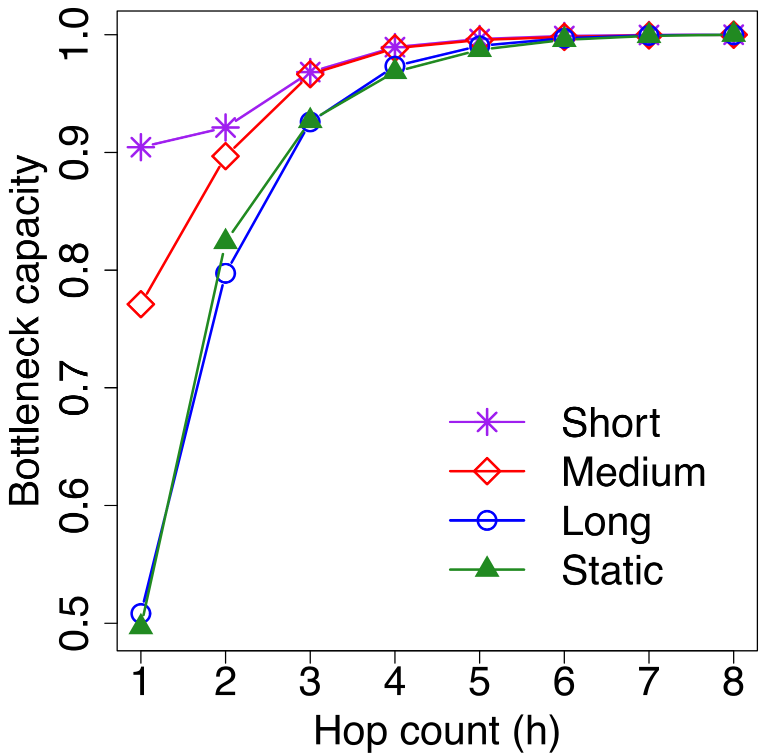
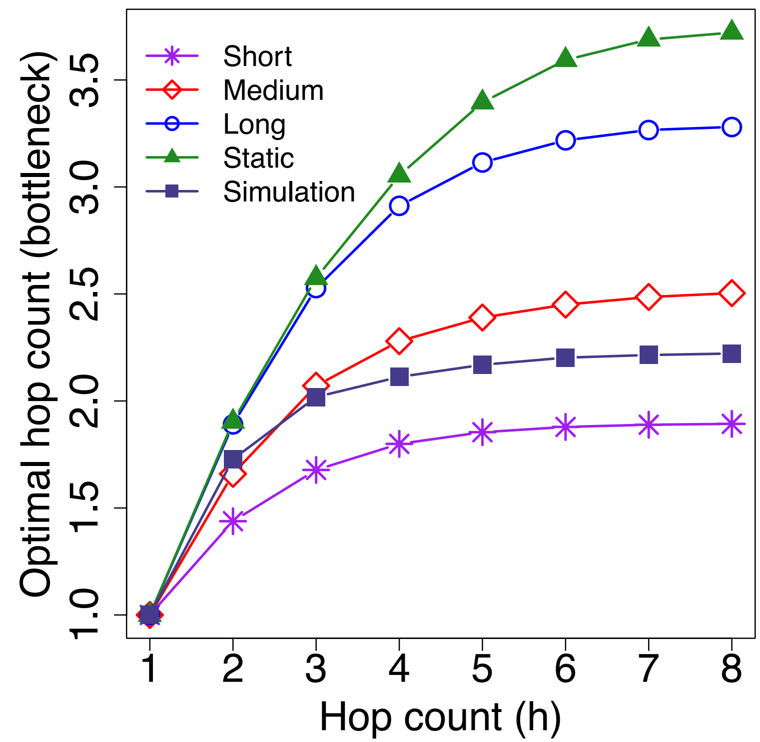


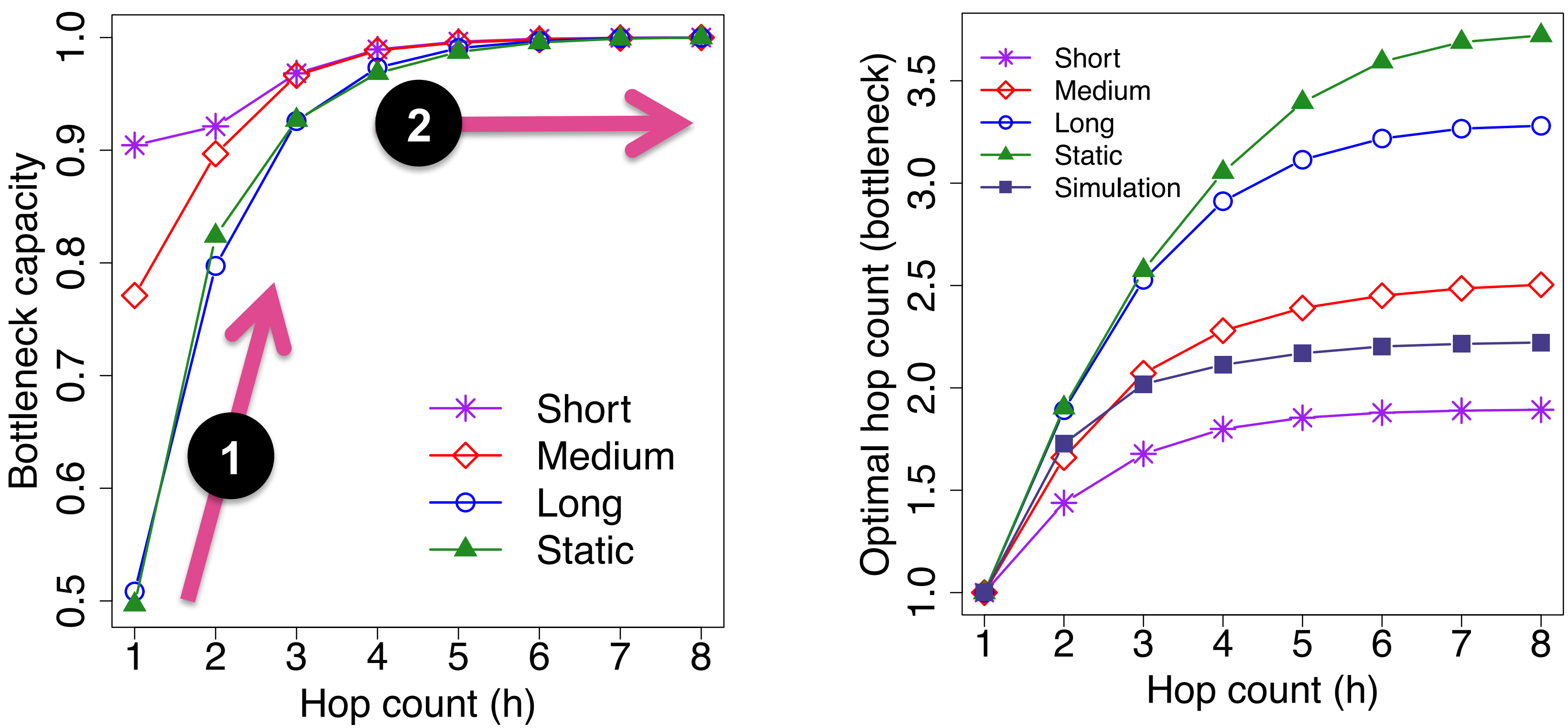


- Highest increase from h=1 to h=2
- After h=4, vanishingly small gain

Bayhan *et al.*, IEEE ICC 2015

Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Network snapshots
Hop count vs. capacity



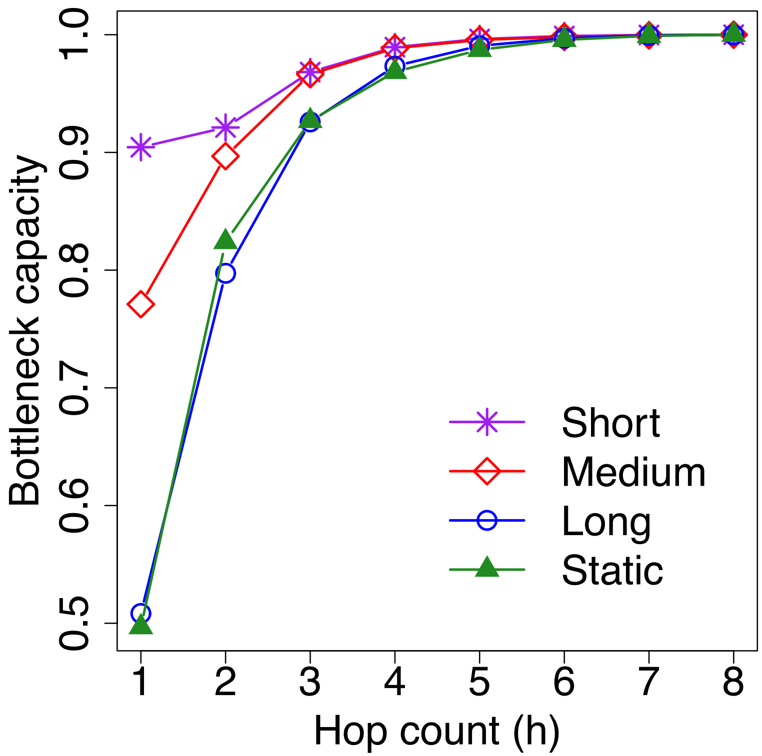
1 Highest increase from h=1 to h=2

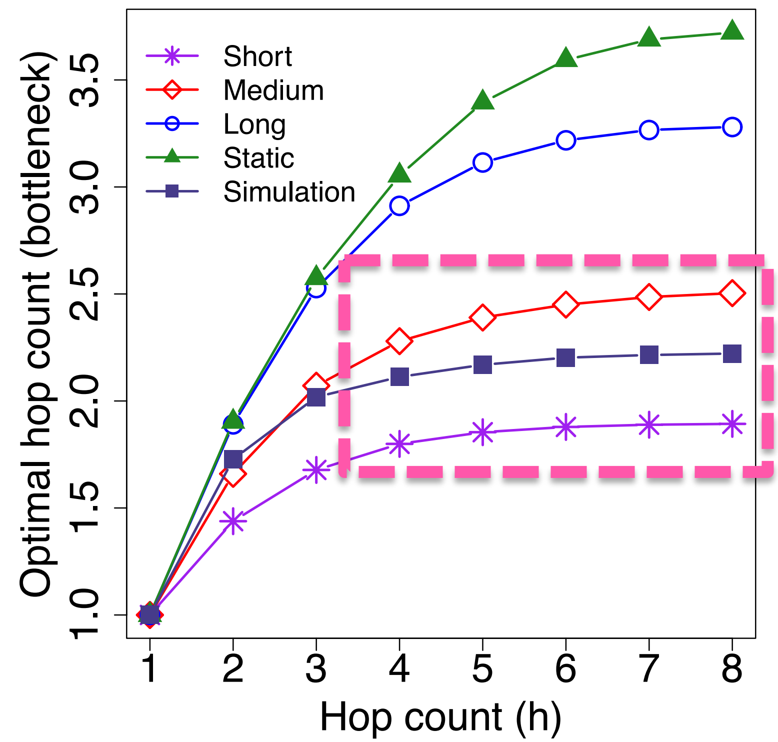
2 After h=4, vanishingly small gain

Bayhan *et al.*, IEEE ICC 2015

Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Network snapshots
Hop count vs. capacity

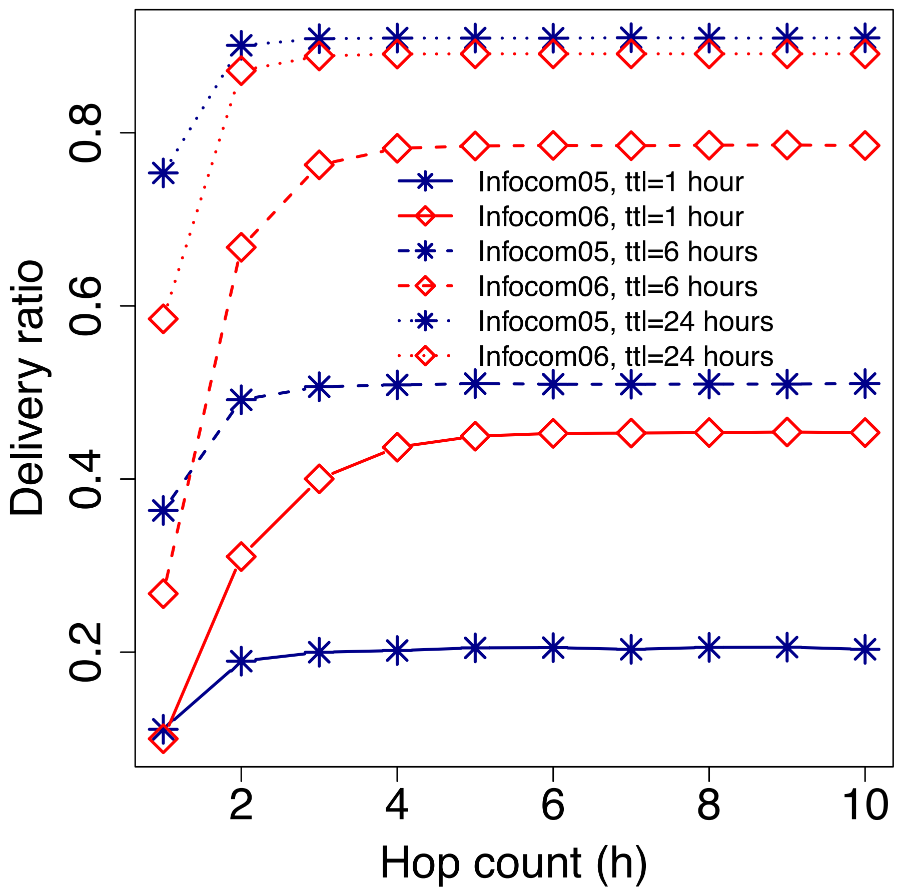




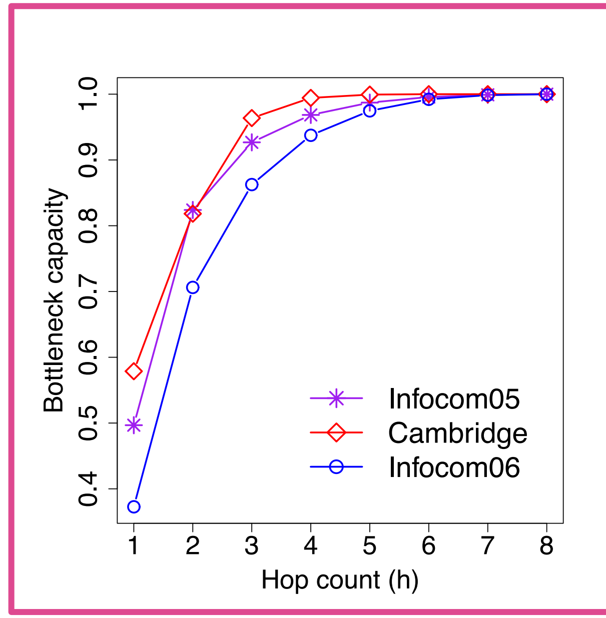
- Short and medium aggregation windows closer to reality

Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Simulations



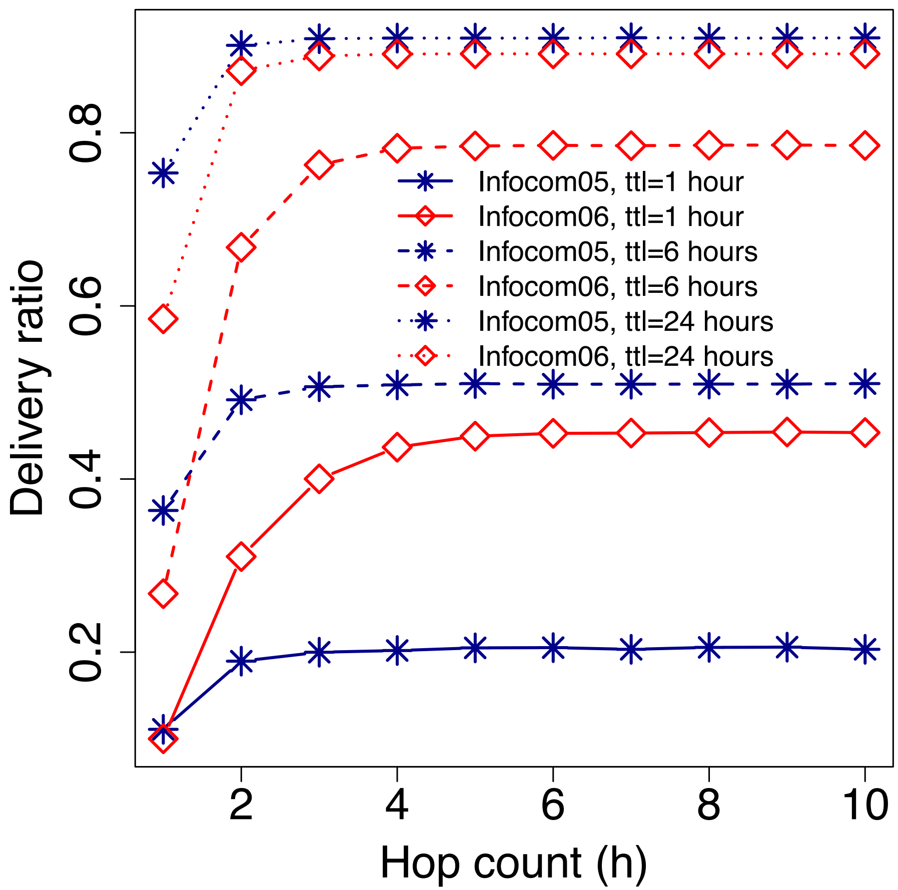
AHOP analysis



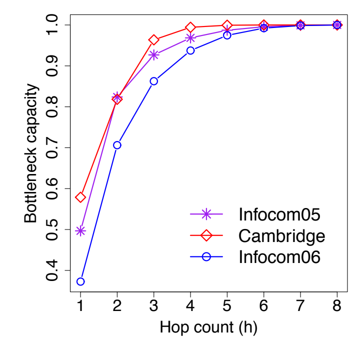
Bottleneck capacity: inverse of number of encounters

Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Simulations



- Agrees our previous analysis
- Trend is the same
  - **h=2** highest improvement
  - **h>4** stability



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Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Simulations
Delivery delay and path lengths

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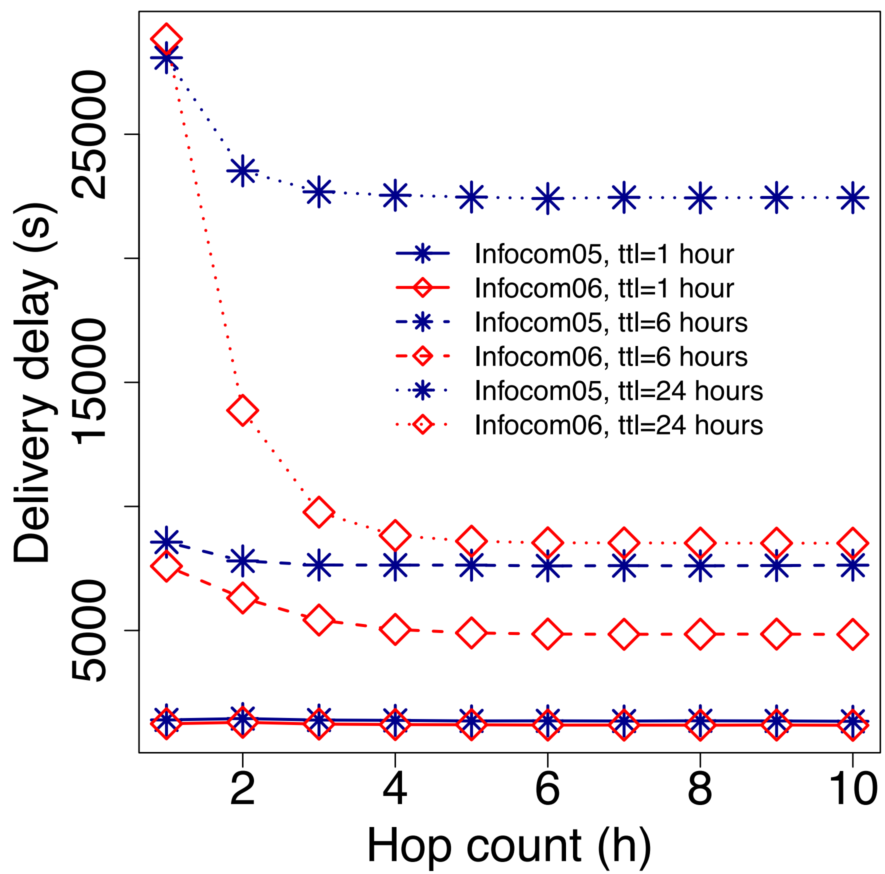
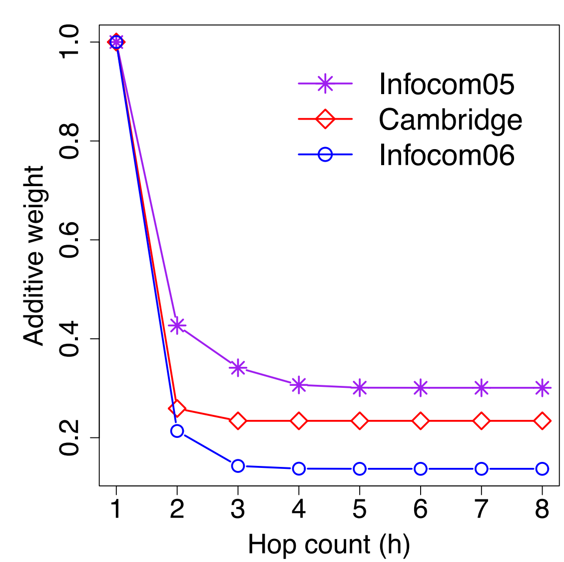


AHOP analysis



Additive weight: inter-contact time

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Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

Summary

Effect of hop count

- Capacity of the studied human contact networks increases significantly with h>=2
- Improvement vanishes after h=4

Effect of analysis approach

- Static graph approach overestimates connectivity and performance
- Time window of the aggregation should be paid attention to

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Source node	Destination node	Relaying nodes	Hop limit

Thank you

Reading list

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- Guérin, Roch, and Ariel Orda, "Computing shortest paths for any number of hops." IEEE/ACM Transactions on Networking (TON) 10.5 (2002): 613-620.
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Analysis of Hop Limit in Opportunistic Networks by Static and Time-Aggregated Graphs

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***Abstract*—Hop count limitation helps controlling the spread of messages as well as the protocol complexity and overhead in a distributed network. For a mobile opportunistic network, we examine how the paths between any two nodes change with increasing number of hops a message can follow. Using the *all hops optimal path* (AHOP) problem, we represent the total delay of a route from a source node to a destination node as *additive weight* and use the number of encounters as a representation of *bottleneck weight*. First, we construct a *static (contact) graph* from the meetings recorded in a human contact trace and then analyze the change in these two weights with increasing hop count. Alternatively, we aggregate all the contact events in a time interval and construct several time-aggregated graphs over which we calculate the capacity metrics. Although, we observe differences in the properties of the static and the time-aggregated graphs (e.g., higher connectivity and average degree in static graph), our analysis shows that second hop brings most of the benefits of multi-hop routing for the studied networks. However, the optimal paths —path that provides the most desirable**

networks (e.g., short contact duration). A less greedy solution is *hop-limited routing* [3], [4] which limits the journey of a message in the network to maximum h hops. More sophisticated protocols aim to balance the tradeoff between delivery ratio and resource consumption by tuning the protocol parameters, e.g., the maximum number of replications [4], lifetime of a message [5], replication/forwarding logic [6], and so on. However, no matter how optimized the protocol is, the performance of a mobile opportunistic network also strongly depends on the *node mobility*. More specifically, two properties related to node mobility are paramount: *contact duration* and *inter-contact time duration*. Contact duration is the time two nodes stay connected while inter-contact time is the time elapsed between two consequent contacts of two particular nodes. Both determine the transmission capacity (i.e., how much data can be transmitted) as well as the speed

Available at
http://www.hiit.fi/u/bayhan/

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17:15-18:00 ICC Capital Hall Interactive 2